Available online at www.sciencedirect.com
ScienceDirect
Physics Procedia
Physics Procedia 56 (2014) 458 – 466

8th International Conference on Photonic Technologies LANE 2014

Laser beam oscillation strategies for fillet welds in lap joints

Alexander Müller[a,*], Sven-F. Goecke[a]; Pravin Sievi[b], Florian Albert[b], Michael Rethmeier[c]

[a]*University of Applied Science Brandenburg; Brandenburg an der Havel, Germany*
[b]*Scansonic MI GmbH, Berlin, Germany*
[c]*Federal Institute for Materials Research and Testing, Berlin, Germany*

Abstract

Laser beam oscillation opens up new possibilities of influencing the welding process in terms of compensation of tolerances and reduction of process emissions that occur in industrial applications, such as in body-in-white manufacturing. The approaches are to adapt the melt pool width in order to generate sufficient melt volume or to influence melt pool dynamics, e.g. for a better degassing. Welding results are highly dependent on the natural frequency of the melt pool, the used spot diameter and the oscillation speed of the laser beam. The conducted investigations with an oscillated 300 µm laser spot show that oscillation strategies, which are adjusted to the joining situation improve welding result for zero-gap welding as well as for bridging gaps to approximately 0.8 mm. However, a complex set of parameters has to be considered in order to generate proper welding results. This work puts emphasize on introducing them.

Peer-review under responsibility of the Bayerisches Laserzentrum GmbH

Keywords: laser beam welding; gap compensation; process monitoring and control; system technology; automotive application

1. Introduction

Oscillated power beam processes have proven the ability to affect the inner weld seam quality, the dilution degree within the melt pool and to influence the welds surface appearance in several investigations [1], [2], [3], [4].

Obtained welding results are dependent of a multitude of parameters. As actively adjustable parameters the welding speed, laser power, spot diameter, beam oscillation frequency and amplitude are identified. Whereas the

* Corresponding author. Tel.: +49-(0)3381-355316 ; fax: +49-(0)3381-355199 .
E-mail address: muelleal@fh-brandenburg.de

Peer-review under responsibility of the Bayerisches Laserzentrum GmbH
doi:10.1016/j.phpro.2014.08.149

natural frequency of the keyhole geometry and the melt pool, the gap height between steel sheets and contaminations of any kind are to be regarded as passive factors.

In previous reports it has been shown that welding with an oscillated 300 µm spot generates more molten material compared to commonly used welding spots of 600 µm. Deductively, the process efficiency increases due to multiple reflections of the laser beam within the melt pool, which is also shown by [5].

Within the welding speed range used in body-in-white applications (2 – 10 m/min), [6] identifies three welding regimes. Below 5 m/min, a rather large melt pool is formed around the keyhole. The keyholes surface shape is circular and its volume compares to a cylinder. The melt pool surface shows chaotic fluctuations and large swellings. With increasing weld speed, the cross section geometry changes from bulgy to narrow. The metal vapour flare oscillates strongly around the centre line of the laser beams inclination angle. Between approximately 6 m/min and 8 m/min single, large melt waves occur at the backside of the keyhole. These waves flow back and forth through the melt pool and cause the keyhole to collapse periodically. The tilt angle of the keyholes front wall increases steadily, which leads to a primary energy input at the front. A stabilisation of the metal vapour flare, which stands upright to the front wall, is obtained. Above 9 m/min, an oval opening of the keyhole is observable. Weld pool oscillations and swellings decrease. Besides the heated keyhole front wall the backside gets heated as well. Two metal vapour flares can be identified. One directed forward the other directed backwards to the welding direction.

Analytical, numerical and experimental works on keyhole and melt pool oscillations were compared by [7] in detail. Identified keyhole frequencies range from 1 kHz to > 3 kHz, melt pool frequencies range from 100 to 600 Hz. One possibility to determine oscillation frequencies is to define the volume and viscosity of the melt, since they directly affect the damping behaviour of the excited melt pool, as the surface tension does, too. The surface tension of the melt is defined by the material composition, which, referred to [8], is a function of surface temperature T and concentration c of the alloying elements or surface impurities. Furthermore, the surface tension influences the melt pool flow. This is, for example the main reason for melt pool shapes in GTA welding [9]. The surface tension among itself is changed by surface-active elements such as oxygen, sulphur and arsenic [10].

Approaches on modelling surface tension effects relate to laser cutting [11] or bead-on-plate runs [12]. Compared to the above mentioned investigations all alterations in alloy composition, due to melt flows and burning of alloys and radius curvature changes of the melt pool surface, do not allow transferring the effects precisely to fillet welding in lap joints. In principle, the surface tension of iron-based materials is the highest at the weld pool edges. At this interface between liquid and solid material, the heat conduction is superior to the one in the melt pool middle.

Laser beam oscillation provides the possibility, to deposit heat space- and time-resolved. However moving the beam through the work piece transversal or longitudinal to the actual welding direction also induces melt flows, which themselves transport heat and have a back coupling to temperature gradients. This work aims at identifying potentials in which ways laser beam oscillation can be used for fillet welding in lap joints. The conducted investigations focus on laser beam welding with an oscillated 300 µm spot with the aim to bridge gaps up to 1 mm at fillet welding in lap joints. This gap size partially occurs in automotive body-in-white manufacturing [13].

Preliminary investigations on the process efficiency of oscillated laser beam welding have been presented in [14]. It is proven that when comparing welds joined with equal oscillation amplitudes the sinusoidal profile shows the largest melt pool formation in contrast to triangular or square shaped oscillation profiles. For that reason investigations focus on sinusoidal oscillation profiles.

2. Experimental Setup

For experimental investigations a beam guiding system of company Scansonic MI GmbH was used (Fig. 1, left). The optics possesses of an integrated seam tracking system based on the laser triangulation principle. Three seam tracking laser lines are projected (1) to the work piece joint, whose reflections are then detected and processed by a camera, installed behind a semi-transparent mirror inside the optical path (2). With the calculated offset position between focus and seam position an automatic beam positioning takes place by the pivoted deflection mirror (P_y). The triangulation camera also measures the gap height and setting angles of the optics in reference to the work piece.

Two additional oscillation scanners (M_x; M_y) were integrated to create one- or two-dimensional oscillation profiles superimposed to the welding direction. The scanners movement accuracy was tested by irradiating a CCD device. The optical path has an aperture of 46 mm. The scanners are synchronized to each other’s movement. The beam guiding system has a focal length of 500 mm. Due to the post objective scanning setup the active working distance is 326 mm. A 5 kW disk laser with a beam parameter product of 4 mm × mrad and a fibre of 100 µm core diameter were used. The resulting Rayleigh length is 5.57 mm. The focus position was set to the lower sheets surface and kept constant by an automatic focusing module. To prevent possible movement vibrations of the robot system, the optics position was maintained and the work piece moved by a linear axis (Fig. 1, right). For process evaluation purposes a high-speed camera of type MotionBLITZ EoSense mini2 was attached to the optics. The coaxially acquired image is filtered by a bandpass filter of 808 nm with a half width of ± 10 nm. There is no illumination used which is why the recorded images show the thermal emissions of the process.

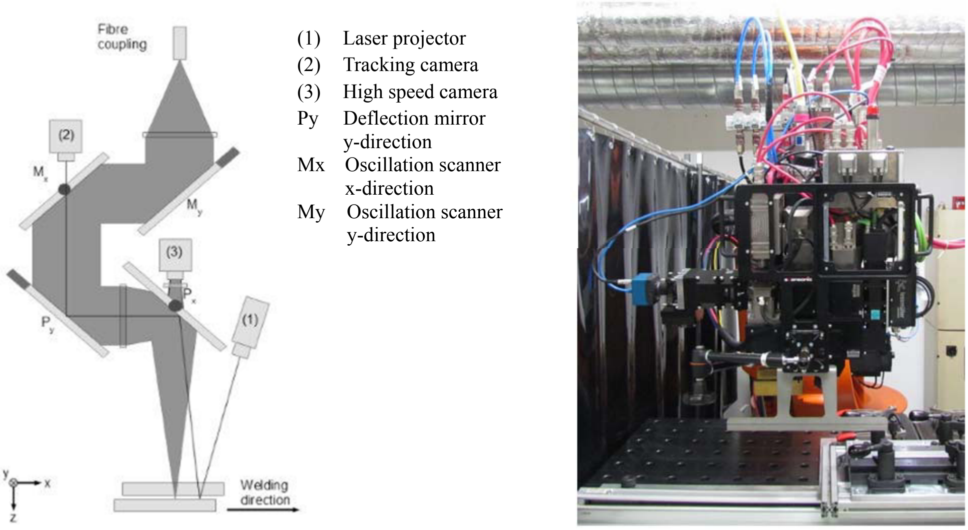


Fig. 1. Left: schematic overview of laser optics system with partly integrated joint tracking system, right: experimental setup on robot with linear axis underneath.

2.1. Bead-on-plate investigation

In the introduction was depicted that disturbing melt swellings take place in industrially used welding regimes. The resulting collapses of the keyhole often go along with melt ejections, spatter and undesirable weld appearances. Therefore, attention needs to be given to frequency dependent changes of this behaviour. For an evaluation of the ejection behaviour an experiment was set in which non-oscillated and oscillated welding with 300 µm spot were compared. The energy input per unit length was kept constant at 30 J/mm, the welding speed was increased from 1 to 10 m/min. Furthermore, the overlapping degree of the welding spots diameter, at each oscillations zero crossing, was set to be 50 %. For example, when welding with a speed of 2.5 m/min, an oscillation frequency of 139 Hz was applied, for 6 m/min – 335 Hz; 10 m/min – 555 Hz. The oscillation amplitude was set to 0.15 mm.

All welds were carried out on one steel sheet sample of grade S355 with a milled surface and thickness of 9.7 mm. For statistical validation three equally long sections (1 mm) within one weld were evaluated for variance and standard deviation. A distance of 4 mm from the beginning and prior to the end is not considered for counting. The statistical repeatability for this type of welds was investigated preliminarily. It was found that for n = 5 all counted emissions lay within a 95 % confidence belt.

2.2. Geometrical model

To transfer oscillation parameter findings from the bead-on-plate investigation to fillet welding in lap joints some preconditions need consideration. Research on the lateral melt off of the upper sheet in lap joint welding, e.g. , defines the incidence angle and position of the laser beam to be the primary influence factor for forming a continues fillet weld. Based on developed geometrical models, starting parameters were chosen. In this regard the oscillation amplitude - in transversal direction to the welding direction – was used to compensate for the calculated offset distance. However, amplitude adjustments were limited to 2x focus diameter because of the expected decreasing in coupling efficiency and formation of unwanted weld pool cross-section when exceeding this range .

Fig. 2 shows the importance of adjusting the proper position of the laser beam subject to incidence angle, material thickness (d_{OB}), gap height (h_S) and focus diameter.

As a first approximation, the area of an ideal fillet weld with an effective throat thickness of 0.7x d_{OB} is a set of conditions of how much material has to be molten off from the upper sheet. Under the preference of a lateral incidence angle of 10°, calculatedly gaps to a height of 0.3 mm are bridgeable without a lateral repositioning of the beam.

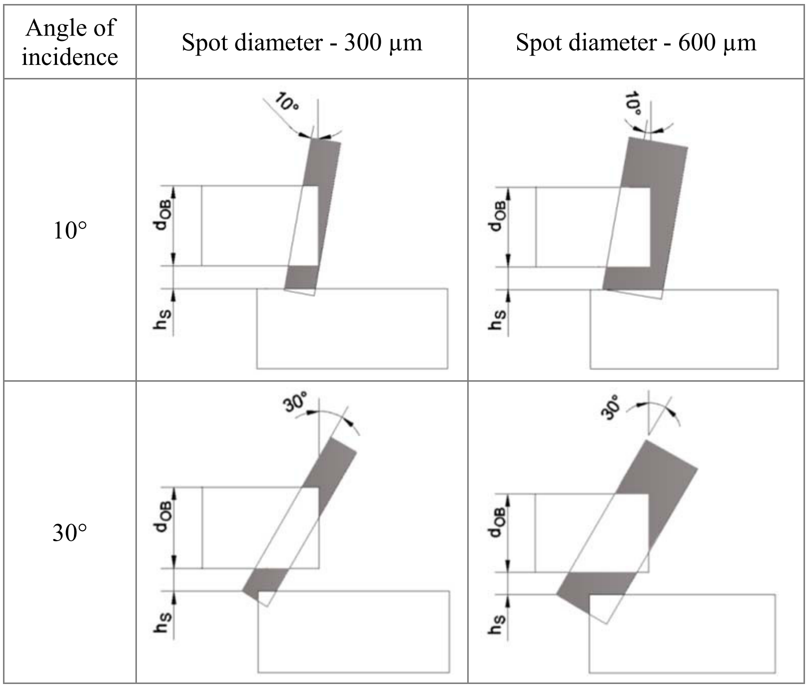


Fig. 2. Geometrical comparison of interaction areas of 300 µm & 600 µm beam diameter for welding 0.8 mm steel sheets – cross section view.

It is visualized that a 600 µm spot diameter interacts with a larger work piece area than is needed for shaping a fillet weld. Actually, when welding zinc coated steel sheets, a 600 µm spot (Fig. 2, Fig. 2. Geometrical comparison of interaction areas of 300 µm & 600 µm beam diameter for welding 0.8 mm steel sheets – cross section viewup, right) evaporates more zinc and therefore produces more process affecting zinc vapour than is wanted. Though, when using a 300 µm spot, increases of the lateral incidence angle of the laser beam need compensation through offset shifts to the lower steel sheet (Fig. 2, down, left).

For the classification of experimental welding results, visual techniques were used. The spatter behaviour was analysed by the help of high speed videos and the surface appearance by manual assessments of the welds. The main criterion hereby was a continuously closed fillet weld without pores or lack of fusion. In addition, as a demand from automotive manufacturing no full penetration welds were allowed. Here zinc coated material of type H260LAD + Z100 was used, a degassing gap of 0.2 mm height was set by a gauge plate to avoid unwanted back coupling effects of produced zinc vapour. The base materials chemical composition is listed in Table 1.

Table 1. Alloy composition of H260LAD.

Element	Fe	C	Si	Mn	P	S	Cr	Mo	Ni
Average content of three consecutive measurements	bal.	0.082	0.0076	0.381	0.0139	0.0092	0.0281	0.0036	0.0202
Element		Al	Cu	Nb	Ti	V	W	B	N
Average content of three consecutive measurements		0.070	0.0209	<0.0002	0.0027	0.0009	0.0019	0.0003	0.0265

3. Results and Discussion

The process comparison between oscillated and non-oscillated (300 µm spot) bead-on-plate runs reflects a clear increase of spatter formation for oscillated welding. However, when separating the spatter dimensions in small (< 0.3 mm) and large melt ejections (> 0.3mm) an advantageous characteristic is revealed. It was found that mainly large ejections cause severe process faults such as pores and lack of fusion, whereas small ejections usually show low interaction with the process itself. Fig. 3 illustrates the spatter and ejection behaviour of size > 0.3 mm.

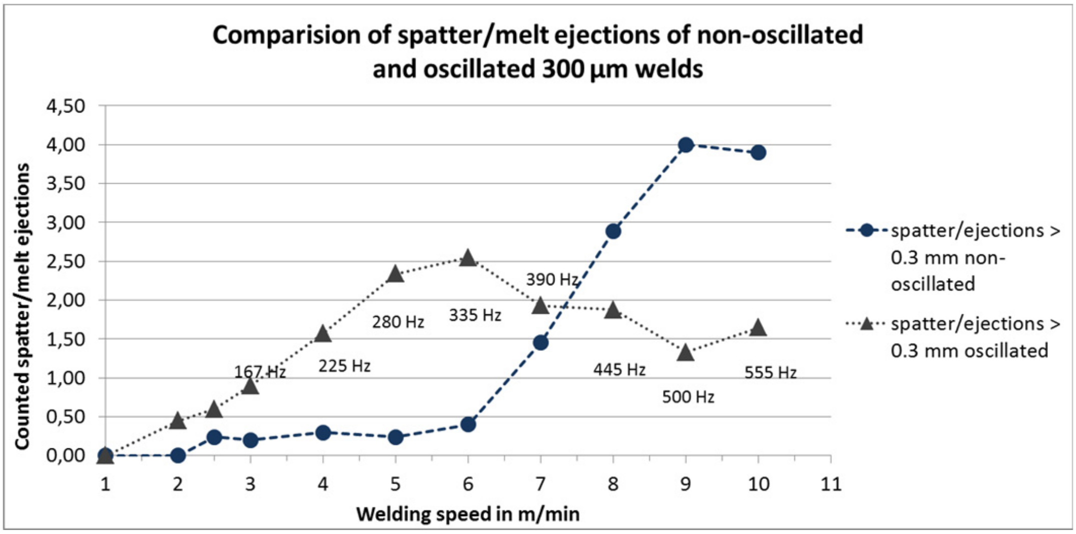


Fig. 3. Comparison of process emissions - non-oscillated and oscillated welds with a focus diameter of 300 µm, max. standard deviation = 0.14.

Spatter and melt ejections in oscillated welds generally take place at the reversal points of the beam movement. The metal vapour flare oscillates equally with the applied beam oscillation. Reaching a welding speed of 3 m/min the mean beam velocity is 9.44 m/min. Until that point, a similar curve progression in terms of large ejections is observed. It is assumed, that between 3 m/min and about 7 m/min welding speed, the predominant factor for spatter ejection results out of a the sudden change of the keyhole wall heating that origins at the oscillations reversal points. Above this welding speed the occurring temperature changes between the irradiated areas of the keyhole wall decrease, hence lower temperature gradients occur and a more stable keyhole is maintained. In the range of approximately 7.5 m/min to 10 m/min, the curve of “spatter/ejections > 0.3 mm oscillated” does not increase further and as a result goes below the non-oscillated weld curve. However, a direct correlation of applied frequencies to spatter and melt ejection behaviour is not possible, due to changing weld regimes. However it becomes obvious, that the effects that coincidences with a keyhole collapsing (large melt ejections) are reducible.

3.1. Fillet welding in lap joints

Comparative to the above findings, the frequency range was extended to 1000 Hz while maintaining a constant welding speed of 2.5 m/min. A nameable reduction in swellings, fluctuations and spatter/melt ejections was observed in frequency areas/ranges of 200 Hz; 600 – 650 Hz and 750 – 900 Hz. Mismatches on the found frequency regions, compared to the bead-on-plate investigations, are an effect of changing melt pool volumes, which arise out of different heat conduction conditions and melt viscosities. A direct comparison with material DX56D of same dimensions as H260LAD also showed shifted frequency ranges but did confirm stabilising effects on the melt pool within certain frequency ranges. For that reason, it can be stated that every material will show different oscillation behaviours if excited by beam oscillation.

Analysing the spatter and melt ejection behaviour in fillet welding in contrast to bead-on-plate runs, it is found that spatter and melt ejections mainly occur at the oscillations reversal point that is facing the joint edge. An explanation for that is that the energy deposited in this area cannot flow into bordering material, which leads to vaporisation of material at the upper sheets edge area. In this moment, the beam simultaneously vaporises zinc from the lower steel sheet, which enhances spatter formation. The effect is reinforced by the characteristic of a sinusoidal function itself. It deposits more energy into the work piece at its reversal points than in between. Independent from that the reversal point that lies opposite of the joint does not show spatter or melt ejections. The deposited energy can flow into the work piece and is additionally dissipated by a melt current that flows along the upper sheets edge.

Despite the illustrated increase of spatter formation, good welds are obtainable within the process zones depicted in Fig. 4. The Figure shows the minimal and maximal laser power necessary for proper welds at different welding speeds. Furthermore it shows the decreasing process window in terms of gap bridgability.

Corresponding weld outcomes and an overview of proposed oscillation strategies are illustrated in Table 2. It is shown that precise positioning of the laser beam enables gap bridging without oscillation strategies to gap sizes of approximately 0.3 mm. Gaps exceeding this limit can be closed by applying a transversal (meaning an oscillation in y-direction) oscillation strategy. This technique can be used to gap sizes of 0.6 mm.

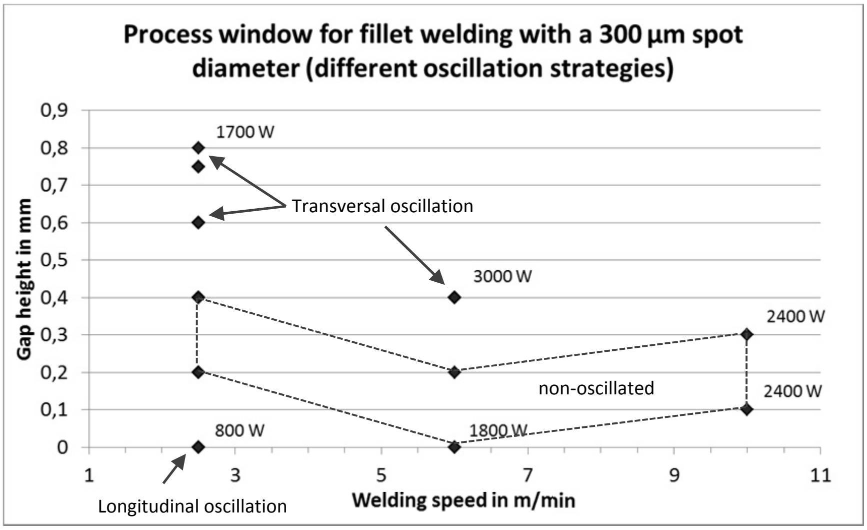
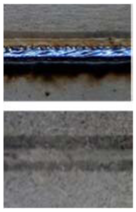
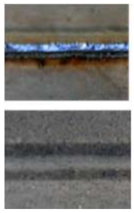
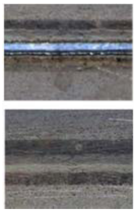
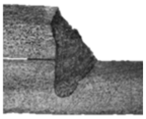
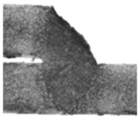
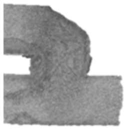
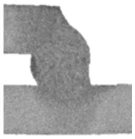
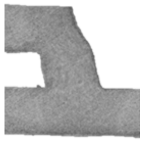
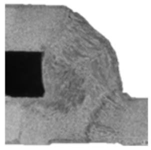


Fig. 4. Validated process zones for different oscillation strategies with 300 µm laser spot.

Table 2. Oscillation strategies overview.

Gap height	< 0.05 mm	0.05 mm– 0.2 mm	0.2 mm – 0.4 mm	0.4 mm– 0.6 mm	0.6 mm– 0.7 mm	> 0.7 mm
Oscillation strategy	Non-oscillated & longitudinal	Non-oscillated & transversal	Non-oscillated & transversal	Transversal	Transversal	Transversal
Front and back side of sample						
Cross-section view [v_S – 2.5 m/min; H260LAD] -						

Alongside the above findings, a more dominant effect on forming proper fillet welds could be identified. Ensuring a continuous lateral melt off is done by maintaining a temperature gradient in the process zone that counteracts material specific surface tension. If the temperature gradients fluctuate above a certain level, droplet formation at the edge of the upper sheet is initialised. Surface tension force σ then exceeds gravitational force g, acting on the melt, resulting in pores and lack of fusion. This time and energy dependent effect can only be balanced by a combination of measures. E.g., it is possible to adjust the laser power and welding speed or the laser power and spot size.

3.2. Droplet formation

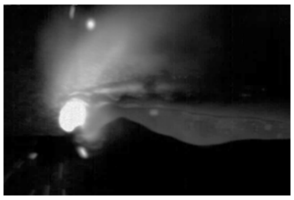
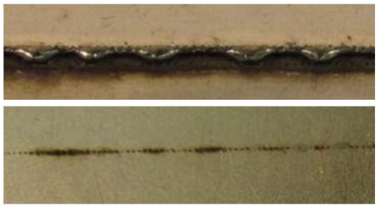
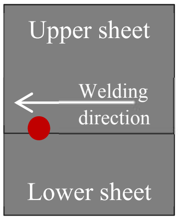
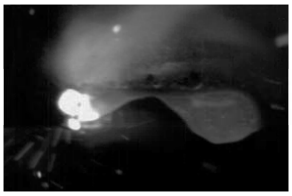
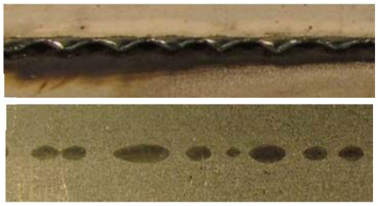
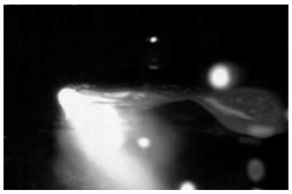
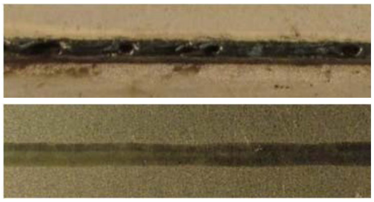
There are three different stages of droplet formation that can be distinguished. Within the stages, a number of magnitudes are observable. We set the experiment at a boundary condition of a gap height 0.4 mm and welding speed of 6 m/min. Oscillation frequency, offset to the upper steel sheet and laser power were varied. Welding outcomes are displayed in Table 3.

Stage 1 – The upper sheet is only partially molten. The resulting droplets are sustained and thin in crosswise dimension. A rather large channel of molten material remains between the droplets. Only some bonding points between the sheets and minimal penetration alongside the weld is identifiable at the back side of the lower sheet. Since a farther positioning to the upper sheet would cause square butt welds, this state is called “pre-square-butt weld stage”.

Stage 2 – The upper sheets edge is completely molten off but not enough laser power and material for gap bridging is provided. Droplets have a more circular shape than in the previous stage and regularly bond to the lower steel sheet. The thermal high speed image shows a high amount of heat remaining inside the droplet. There is only a small channel of melt in between the droplets. Through this channel a continuous melt flow to the trailing droplet is visual. When droplets reach a specific volume/weight, bonding to the lower sheet takes place. In this instance, stored heat dispenses into the lower sheet. The surface tension force then increases rapidly and eventually closes the melt channel. At this point the build-up of a new droplet starts. This procedure creates typical spot heat marks on the bottom side of the lower sheet. This state can be seen as the “droplet-stage”.

Stage 3 – Complete melt off of the upper sheet, sufficient laser power is applied but the positioning to the upper sheet is not properly adapted. Due to the higher energy input, a more stable temperature gradient is formed. The molten material does not form droplets, but mainly rectangular areas that regularly bond to the lower sheet. However, not enough material is provided to completely bridge the gap. Since the process strives for stability it is called the pre-bridging state.

Table 3. Droplet formation stages.

Stage	Experimental setup	High speed image	Front and back side of sample	Parameter
1				PL – 1900 W f – 150 Hz Beam offset to upper sheet – 0.15 mm
2				PL – 2200 W f – 300 Hz Beam offset to upper sheet – 0.2 mm
3				PL – 2600 W f – 400 Hz Beam offset to upper sheet – 0.2 mm

4. Conclusions

The work shows that welding with a small focus diameter and significantly reduced laser power, compared to conventional applications, becomes possible. However, beam oscillation does not have to be applied for this welding setup. In reverse exact knowledge of the behaviour of the material is necessary to use beam oscillation reasonably. For zero-gap welding, which usually is carried out as a full penetration weld, a major improvement is the reduction of the interaction zone of the laser beam with the zinc coated steel zone. Out of this less zinc is vaporised, while still adhering to a sufficient throat thickness.

Furthermore a gap dependent process strategy is proposed, which, up to a gap height of 0.3 mm, does not use beam oscillation. However beam oscillation can bridge gaps, in the given setup and material combination to about 0.4 mm at 6 m/min (Fig. 4), without further time-energy coupled measures, meaning adjustments of laser power or welding speeds.

Weld regime dependent melt flows, oscillation profiles and material characteristics have severe impact on the melt off behaviour of the upper steel sheet and leave little room for generalised conclusions. Ensuring an active droplet detachment is of essential meaning to create continuous welds.

Acknowledgement

The authors would like to thank the German Federal Ministry of Education and Research (BMBF) for the support of the carried out research work within the scope of the program “Research at Universities of Applied Science“, as directive of “Qualification of young engineers”.

References

[1] Z. Sun and R. Karppi, “The application of electron beam welding for the joining of dissimilar metals: an overview,” Journal of Materials Processing Technology, pp. 257-267, 27 May 1996.

[2] F. Albert, A. Müller and P. Sievi, “Laserstrahl-Remoteschweißen mit Nahtführung und örtlicher Strahloszillation – eine Wirtschaftlichkeitsbetrachtung,” Laser Technik Journal, no. submitted, 2013.

[3] J. Standfuß, A. Klotzbach, M. Heitmanek and M. Krätzsch, “Laser beam welding with high-frequency beam oscillation: welding of dissimilar materials with brilliant fiber lasers,” in International Laser Symposium Fiber & Disc (FiSC), Dresden, 2010.

[4] O. Meier, “Hochfrequentes Strahlpendeln zur Erhöhung der Prozessstabilität beim Laserstrahlschweißen,” Laser Zentrum Hannover e.V., Hannover, 2005.

[5] M. G. Müller, Prozessüberwachung beim Laserstrahlschweißen durch Auswertung der reflektierten Leistung, München: Herbert Utz Verlag, 2002.

[6] R. Fabbro, “Melt pool and keyhole behaviour analysis for deep penetration laser welding,” Journal of Physics D: Applied Physics, 15 October 2010.

[7] J. Volpp and D. Freimann, “Indirect measurement of keyhole pressure oscillations during laser deep penetration welding,” in 32nd International congress on applications of lasers & electro-optics, Miami, FL USA, 2013.

[8] R. Poprawe, Lasertechnik für die Fertigung, Berlin Heidelberg: Springer-Verlag, 2005, p. 75 ff..

[9] C. Heiple, J. Roper, R. Stagner and R. Aden, “Surface active element effects on the shape of GTA, Laser, and electron beam welds,” Welding research supplement, pp. 72-75, March 1983.

[10] G. Schulze, Die Metallurgie des Schweißens, Berlin Heidelberg: Springer-Verlag, 2010.

[11] E.-H. Amara, K. Kheloufi and T. Tamsaout, “2D Modeling of surface tension effect during laser metal cutting,” in 32nd International congress on applications of lasers & electro-optics, Miami, FL USA, 2013.

[12] A. Siwek, “Model of surface tension in the keyhole formation area during laser welding,” Computer Methods in Materials Science, vol. 13, no. 1, pp. 166-172, 2013.

[13] R. Meyer, Erhöhung der Prozesssicherheit durch Beherrschung der Bauteilabweichung beim Fügen im Karosseriebau, Dresden: TUD, 2012.

[14] A. Müller and S. F. Goecke, “Investigation on laser beam oscillation for fillet welds in lap joints,” in Proceedings of Joining of Materials 17, Helsingor, 2013.

[15] A. Reek, Stragien zur Fokuspositionierung beim Laserstrahlschweißen, Technische Universität München, 2000.

[16] C. Thiel, Hess, Axel, Weber, Rudolf, Graf and Thomas, "Stabilization of laser welding processes by means of beam oscillation," Laser Sources and Applications - Proceedings of SPIE Vol. 8433, 2012.